Domain wall magnetoresistance in a nanopatterned $La_{2/3}Sr_{1/3}MnO_3$ track

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We have measured the contribution of magnetic domain walls (DWs) to the electric resistance in epitaxial manganite films patterned by electron-beam lithography into a track containing a set of notches. We find a DW resistance-area (RA) product of $\sim 2.5 \ 10^{-13} \ \Omega m^2$ at low temperature and bias, which is several orders of magnitude larger than the values reported for 3d ferromagnets. However, the current-voltage characteristics are highly linear which indicates that the DWs are not phase separated but metallic. The DWRA is found to increase upon increasing the injected current, presumably reflecting some deformation of the wall by spin-transfer. When increasing temperature, the DWRA vanishes at $\sim 225K$ which is likely related to the temperature dependence of the film anisotropy.

The influence of magnetic domain walls (DWs) on the electric resistance of ferromagnets has been the subject of numerous studies in the past [1]. At present, DWs are still intensely investigated as they are expected to play an important role in future spintronics devices. For example, it has been shown that DWs can be displaced by spin-polarized currents, which can be used to switch the magnetic configuration of a magnetic trilayer from parallel to antiparallel [2, 3]. Even more, logic circuits based on magnetic DWs have been proposed recently [4].

Most experimental works on the transport properties of magnetic DWs have focused on conventional 3d ferromagnets [1]. In these systems, the DW magnetoresistance (DWMR, defined as the change in resistance between the case where the sample is in a single domain state, with all magnetic moments aligned, and the case where the sample is divided into domains separated by domain walls that electrons must cross) is usually less than 1%, with DW resistance-area (RA) products in the 10^{-19}-$10^{-16} \ \Omega m^2$ range [1]. More recently, the DWMR has also been measured in (Ga,Mn)As [5] and in ferromagnetic oxides like $SrRuO_3$ [6] and manganites [7, 8, 9, 10, 11]. In manganese perovskites especially, the strong interplay between the spin, charge and lattice degrees of freedom [12] is expected to provide an additional richness to the physics of electron transport through DWs [13, 14, 15].

Little is known on magnetic DWs in manganites. Fresnel imaging has been used to measure the width δ of a DW in a 200 nm $La_{2/3}Ca_{1/3}MnO_3$ (LCMO) film, yielding $\delta \simeq 38$ nm [16]. Their contribution to the resistance was measured in patterned LCMO tracks and a RA product of $8 \ 10^{-14} \ \Omega m^2$ was found at 77K [7], which is several orders of magnitude larger than what is found in conventional 3d metals. Estimations based on a simple application of the double-exchange model revealed that the resistivity increase due to conventional Bloch-type DWs cannot possibly explain experimental results [7, 17]. To account for this discrepancy, suggestions that DWs in manganites have an unusual, non-Bloch structure were made [15]. In reference 15 it was predicted that for manganites with intermediate doping level two types of DW may take place. In most of the cases the long-wavelength properties of double-exchange ferromagnets are adequately captured within an effective Heisenberg description and conventional Bloch-type DWs are a stable solution of the corresponding Hamiltonian [18]. However under specific conditions stripe walls, which are composed of two ferromagnetic domains separated by a stripe of antiferromagnetic phase (phase-separated DW), may become more energetically favourable than Bloch-type walls. Provided that such DWs exist, their contribution to the total resistance of the sample should be substantially large, as carrier transport across a phase-separated DW is strongly suppressed due to insulating properties of the antiferromagnetic phase. It was suggested that these phase-separated DW may account for the large DW resistance observed in previous experiments [13, 15]. However no clear evidence of this fact exists.

Here, we report magnetotransport measurements of devices consisting of a track with nanometric notches defined in a $La_{2/3}Sr_{1/3}MnO_3$ (LSMO) epitaxial thin film. In the R(H) dependence of these devices, we observe jumps in the resistance at low magnetic field (H) which we attribute to domain walls. Their RA product is in the $10^{-13} \ \Omega m^2$ range and, remarkably, increases with the applied bias. We argue that in our case the DWs are not of the phase-separated type and should be depinned by critical currents substantially lower than in 3d metals.

LSMO thin films (thickness t = 10 nm) were grown on (001)-oriented $SrTiO_3$ (STO) substrates by pulsed laser deposition [19]. The films are epitaxial as evidenced by X-ray diffraction studies, and their surface shows flat terraces separated by one-unit-cell-high steps. The grain
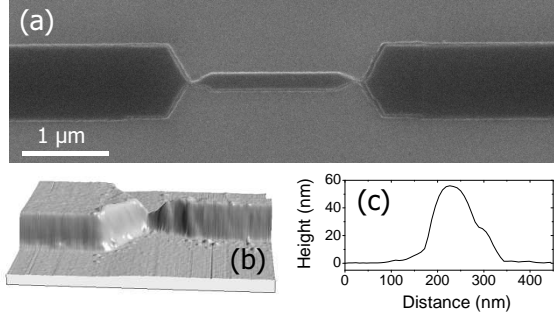
FIG. 1: (a) Scanning electron microscopy image of the device, i.e. the LSMO track covered by the resist, after ion beam etching. (b) AFM image of one of the notches. (c) Profile along the dashed line in (b).

FIG. 2: R(H) curves at 8K and different bias voltages.

size is typically $\sim$100 μm. The Curie temperature (T_C) of the films was 320 K, i.e. slightly lower than the bulk T_C (360K) due to their low thickness [20]. M(H) cycles measured at 10K along different in-plane directions evidenced a biaxial anisotropy, with the easy axes along [110] and [-110] (Ref. 21). The corresponding cubic anisotropy constant was K=9 10^3 Jm^{-3}.

The films were patterned by electron-beam lithography, using a negative resist HSQ-FOX 12. No subsequent annealing was applied. The exposition was performed in a modified field-effect gun scanning electron microscopy (SEM) at 30 keV (see Ref. 21 for details). After exposure, development and ion-beam etching, the $\sim$100 nm thick (insulating) resist was left on the patterned track, although its thickness was strongly reduced at the notches. The devices defined with this process consist of a 350 nm wide and 2 μm long central domain connected on each side to 1 μm wide and 15 μm long tracks by two narrow notches. The track was oriented along the easy [110] direction. The dimensions of the devices were determined in view of micromagnetic simulations results and chosen so as to allow magnetization reversal in the central region at a larger field than in the outer arms. Thus, in a certain field range corresponding to an antiparallel alignment of the central domain magnetization with respect to the magnetization in the outer arms, a DW should be located at each notch. Micronic sputtered Au pads were used as contacts. Figure 1a show a SEM image of one of the devices. Atomic force microscopy (AFM) images (Fig. 1b) and cross-sections (Fig. 1c) of the notches revealed that their width is around w=150 nm.

In figure 2, we show a set of R(H) curves measured at 8K with different applied bias voltages (V_{DC}) for the device of figure 1. When coming from high positive magnetic field to low negative H values a jump ΔR occurs in the resistance (between -100 and -500 Oe). Upon increasing the field further to large negative values, R shows
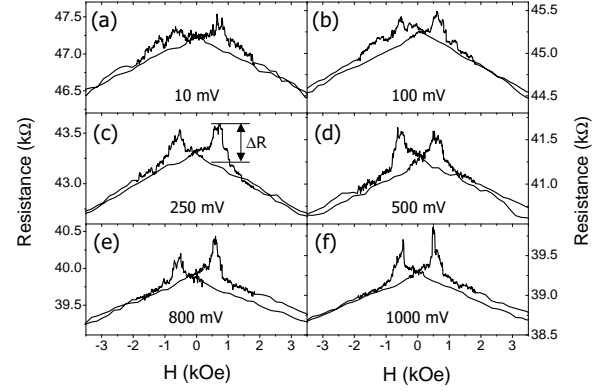
some sharp features and then recovers a low-resistance state at about -1 kOe. A virtually symmetric behaviour is obtained when going back to large positive fields. These jumps are not observed in a track without notches [21]. We also note that at large field, the resistance decreases linearly, which reflects some spin disorder.

We have verified that the typical artifacts that occur in DWMR measurements [1] cannot explain our data. We have measured the MR of a track without notches with the field applied in plane and perpendicular to the track direction. The R(H) is dominated by a linear negative MR in all the field range, as observed at high field in the device R(H) data of figure 2. This indicates that the contribution of AMR is very small (see inset of Fig. 4). As our films are magnetized in plane, we can also discard the contribution of Hall effect. Finally, the Lorentz MR is negligible in manganites due to their very small carrier mean free path ($\lambda \simeq 1$ nm). We thus conclude that the jumps observed in the R(H) cycles most likely arise from the presence of DWs. We can calculate the resistance-area product (RA) for the DWs, assuming they are located at the notches. From the value of ΔR and taking a sectional area of 150×10 nm^2, we find that a DW has an RA of $\sim$2.5 10^{-13} Ωm^2 at 8K and $|V_{DC}|$=200 mV. This is in good agreement with the value reported by Mathur et al [7], larger by several orders of magnitude than what is found for 3d metals, and about 100 times larger than the DWRA in SrRuO$_3$ [6]. Our results thus confirm that DWs in manganites are highly resistive, with RA values several orders of magnitude larger than what is expected from a simple double-exchange model [7].

Further insight on the nature of the DW can be gained from inspecting the I(V) curves of the device. As visible on the inset of figure 3, they are highly linear, with only a small non-linear contribution. This rules out the presence of insulating regions in the track such as grain boundaries or charge-ordered antiferromagnetic stripes that would act as tunnel barriers and thus lead to highly non-linear I(V) curves. We thus conclude that our DWs are not of
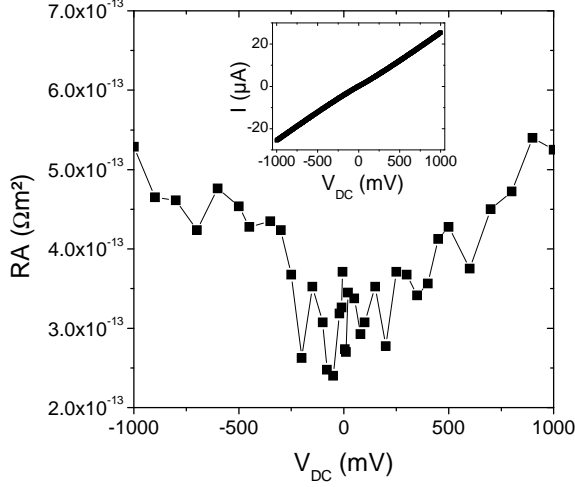
FIG. 3: Bias voltage dependence of the DWRA, at 8K. Inset : I(V) curve of the device.

FIG. 4: Temperature dependence of the DWRA. Inset : R(H) of a track without notches at 8K, 100 mV and with the field applied in-plane and perpendicular to the track direction.

the phase-separated type [13, 15]. The small non-linear contribution is virtually independent of magnetic field and thus probably reflects the existence of localized states related to structural defects created by the lithography process.

Since our data do not support that phase-separated DWs are responsible for the huge resistance of DWs in LSMO, alternative scenarios must be found. It is known that narrow-band manganites can show a metallic behavior at low temperature and have resistivities of up to $\sim 10^5$ Ωcm, i.e. 8 orders of magnitude larger than in LSMO [22]. While the reduction of the double-exchange interaction due to the rotation of moments within the DW is not enough to explain this large DWRA [7], it is possible that within the DW, the conduction band becomes more narrow due the reinforced competition between a weakened double-exchange interaction and super exchange. This may lead to a reduced carrier mobility or to the trapping of some carriers as is thought to occur in narrow-band manganites [22], hence increasing the resistivity.

The thick resist layer left on the patterned track impeded its magnetic imaging. To get a better insight into the micromagnetics of our device, we performed simulations. This study revealed that the DWs pinned at the notches should be of the head-to-head type. As the films are intrinsically very soft, notches may constrain [23] the DWs. The high switching fields found experimentally evidence a significant role of structural defects in the reversal processes. These defects may result in further constriction of the DWs. Details of this study will be given elsewhere [24].

The main panel of figure 3 shows the variation of the wall resistance with bias voltage. Remarkably, the amplitude of DWRA increases upon increasing the bias
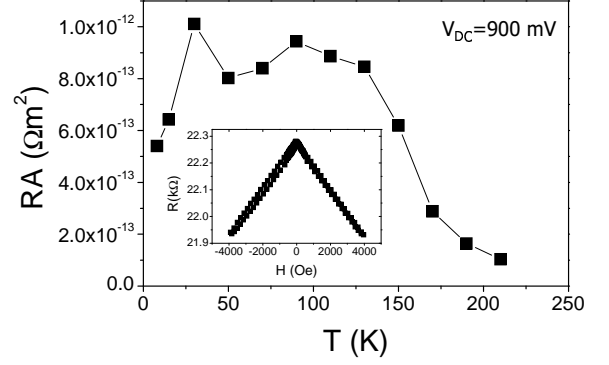
voltage (in absolute value) in the -1V to 1V range, see figure 3. This behaviour is qualitatively very different from that observed in manganite-based tunnel junctions, in which the tunnel magnetoresistance (TMR) is found to decrease with bias, under the influence of electron-magnon scattering and band structure effects [25]. This further precludes the existence of a charge-ordered anti-ferromagnetic core in the DWs. Note that the variation of DWRA we observe here is unlikely to be caused by Joule heating, as the device resistance decreases with increasing bias voltage (see figure 2) while it increases with temperature [21]. A possible explanation is the deformation of the DW under the influence of the injected current, that is the transfer of spin angular momentum from the spin-polarized current to the local magnetic moment. This spin-pressure effect has been predicted theoretically and experimentally observed at current densities of J$\sim 10^{12-13}$ Am^{-2} in NiFe structures [26, 27]. In our case, J is much smaller, on the order of 10^{10} Am^{-2}, but the current spin-polarization in LSMO is almost 100% (Ref. 28) and, as previously mentioned, the DWs are very resistive, so that even a small deformation should produce a visible change of DWRA. We also point out that this observation suggests rather low critical current densities for domain wall depinning and motion in LSMO, as also found by Pallecchi et al [29].

We have also measured the temperature dependence of the DW resistance, see figure 4. ΔR is almost constant up to about 125K and then decreases to vanish around 225K, which is substantially lower than the T$_C$ of the film (300K). In manganites, extrinsic magnetoresistive effects such as powder magnetoresistance [30] or TMR [31] are known to decrease with temperature and disappear at temperatures lower than T$_C$. In the case of TMR, this is ascribed to a reduced T$_C$ at the interfaces between the manganite electrodes and the barrier. Here, a possibility would also be that the manganite in the notches regions has a depressed T$_C$ compared to the rest of the film, due

to size effects or deterioration by the fabrication process. However in that case, a signature of the metal-insulator transition (occurring at T_C in manganites [12]) of the notches should have been observed in the R(T) curve [21]. An alternative explanation resides in the temperature dependence of the biaxial anisotropy constant in LSMO that decreases rapidly with T and vanishes close to T_C [32]. Therefore, the DW is expected to broaden when T increases, which should reduce its contribution to resistance. Temperature dependent magnetic imaging should bring insight on this point.

In summary, we have measured the resistance of magnetic domain walls in a LSMO track containing two ∼150 nm wide notches. We find a DWRA of 2.5 10^{-13} Ωm^2 at low temperature and bias, which increases when increasing the injected current, possibly reflecting the DW deformation by spin-transfer. I(V) curves are almost linear which indicates that the DWs in LSMO are not of the phase-separated type [13]. The DWMR is found to vanish at about 225K, which we tentatively ascribe to the broadening of the DW due to the temperature dependence of the anisotropy constant of LSMO. The next step would now consist in studying the current-induced DW motion in half-metallic manganites. Indeed, the large DW resistivity should make LSMO well suited for testing DW-based logic architectures with resistive readout.

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